Met.O.915
METEOROLOGICAL OFFICE

the meteorological magazine

DECEMBER 1978 No 1277 Vol 107
Her Majesty's Stationery Office

METEOROLOGICAL OFFICE Met.O.915

THE METEOROLOGICAL MAGAZINE

No. 1277, December 1978, Vol. 107

551.501.45:551.521.1

THE DISTRIBUTION OVER GREAT BRITAIN OF GLOBAL SOLAR IRRADIATION ON A HORIZONTAL SURFACE

By J. P. COWLEY

(Meteorological Office, Bracknell)

SUMMARY

A set of linear regression equations between daily global solar irradiation and the duration of bright sunshine is solved for 10 stations in the United Kingdom which record both parameters, and the regression constants are estimated for 40 km square regions over Great Britain. Sunshine data from 132 stations distributed over Great Britain together with measurements of global solar radiation on a horizontal plane at a further 25 stations are used to estimate monthly averaged daily global solar irradiation on a horizontal plane, and a set of monthly maps is presented that shows the variation of this irradiation over Great Britain.

1. INTRODUCTION

A need exists for a knowledge of the variation of solar irradiation at the earth's surface over Great Britain: it is required for hydrological studies when calculating soil moisture deficits, and for building-science studies of the heat gains of buildings, as well as for other applied science studies.

Solar radiation (in the wavelength region 0·3–3·0 μm) is measured directly at only a small number of stations (see Figure 1), and it is therefore not possible to infer directly the irradiation over large areas of Great Britain. However, it is well known that the monthly global solar irradiation on a horizontal surface is closely related to the duration of bright sunshine (Ångström, 1924). In an attempt to describe the distribution of monthly averaged daily global solar irradiation over north-west Europe, Day (1961) used the relatively dense and uniform distribution of sunshine recording stations to estimate the irradiation, using the expression

$$G = G_0[a + b(n/N)], \qquad (1)$$

where G is global solar irradiation,
G_0 is global irradiation above the atmosphere,
n is duration of bright sunshine,
N is maximum possible duration of sunshine, and
a, b are constants.

Day used the radiation data from 17 land stations in the United Kingdom and from 3 ocean weather stations and calculated regression constants a, b for each of them. Since a, b showed no simple pattern of variation he used the regression equation to estimate irradiation at sunshine stations in the vicinity of 11 'parent' radiation stations, using their values of a, b. He was thus able to calculate some 40 estimates that were reasonably uniformly distributed over the British Isles. The major limitation in Day's work was the restricted amount of data, poorly distributed, which was then available.

Collingbourne (1976) produced a set of five maps to illustrate the broad-scale seasonal and geographical variation in monthly averaged daily global solar irradiation over the United Kingdom measured on a horizontal surface. The set was based on solar radiation data alone, and the distribution of stations was close to that used by Day, but the data covered a much longer period. Subsequently, Caton and Smith (1977) have used the radiation data available to Collingbourne in combination with monthly maps of duration of bright sunshine over the United Kingdom (Meteorological Office, 1974), to produce, subjectively, a corresponding series of maps of solar irradiation. These maps contain greater detail than those of Collingbourne, showing such features as the lower levels of irradiation over mid-Wales and the higher ground of the English south-western peninsula that had been indicated more objectively by Day.

In the present work an attempt is made to relate daily global solar irradiation to duration of bright sunshine in an objective way, similar to that used by Day, but using more data, rather than in the more subjective manner of Caton and Smith. Values of the regression constants for 10 radiation stations (indicated in Figure 1) were calculated. It was found that they have both seasonal and geographical variations. Values of the constants were assigned subjectively to 190 square regions of 40 km side that cover almost all the land of Great Britain; these regions are those used by the Agricultural and Hydrometeorological Branch of the Meteorological Office in its computer-based evaporation model for which the constants may be of use when a form of Penman's equation is applied. The sunshine data for 132 stations were used to estimate global irradiation, using the value of the constants appropriate to the location of each station.

It is believed that the present work is superior to that of Day because

(a) more radiation and sunshine stations were considered,

(b) longer durations of measurements were available, and

(c) broad-scale patterns in the constants have been exploited.

It improves on the work of Caton and Smith because the sunshine data have been introduced in a more objective manner; the shapes of the patterns of sunshine distribution have still been heeded, however, on the assumption that the scale of variation of the constants was larger than the inter-station spacing.

2. Relationship between daily global solar irradiation and the duration of bright sunshine

A correlation technique has been developed by the author to estimate the fractional daily global solar irradiation (G/G_0) from the average fractional duration of bright sunshine (n/N). It was found that an expression of the form of equation (1) applies well to partially sunny days, but sunless days form a

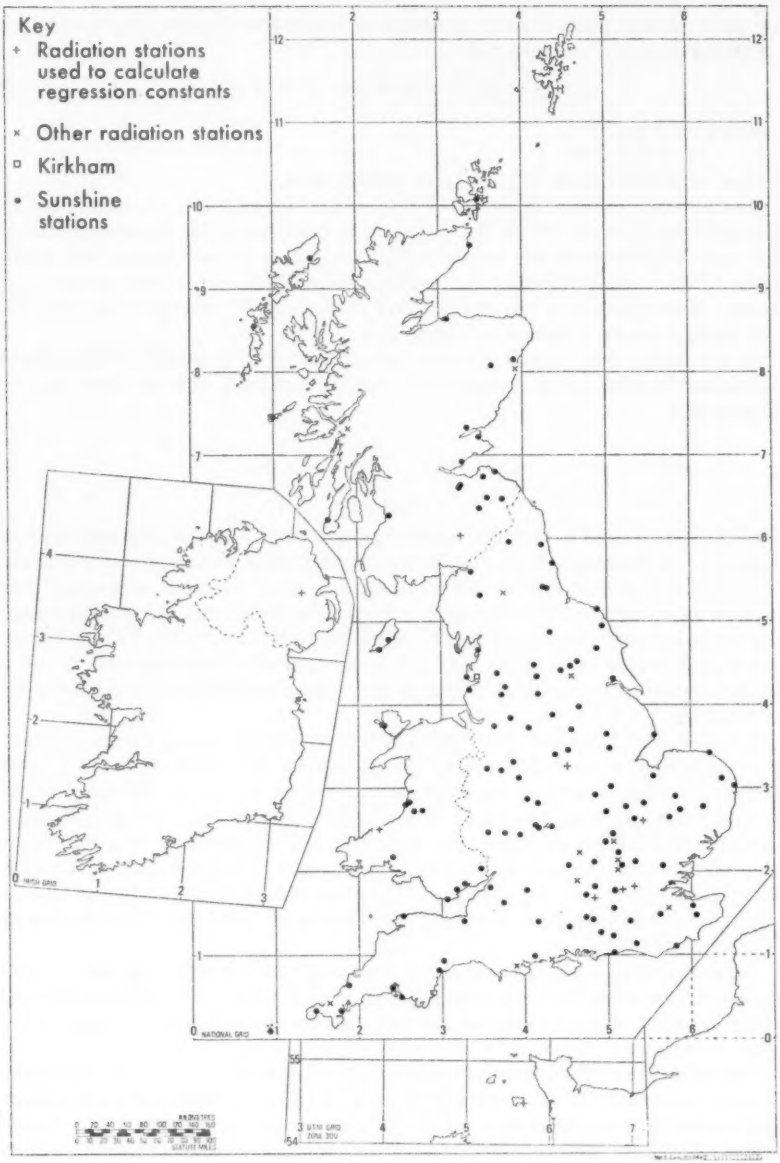

FIGURE 1—DISTRIBUTION OF STATIONS

separate population, being often associated with situations where multi-layered or thick clouds predominate, resulting in lower irradiations. Accordingly a modified equation was adopted:

$$(G/G_0) = \delta[a + b\,(n/N)] + (1 - \delta)\,a', \qquad (2)$$

where $\delta = 0$ if $n = 0$,
$= 1$ if $n > 0$,
and a' = average value of (G/G_0) for sunless days.

In this work, (G/G_0) and (n/N) were calculated for each day; G_0 was based on the solar constant of 1353 W m^{-2}, correction being made for the eccentricity of the earth's orbit about the sun (Cowley, 1976), and N was taken as the astronomical day length allowing for average atmospheric refraction of the solar beam. A comparison of the application of equations (1) and (2) to the data for one station-month is shown in Figure 2(a).

It was shown that there is a lower root-mean-square deviation of data about equation (2) than about equation (1) for all months. This is illustrated in Figure 2(b).

3. Analysis

Values of a, a' and b were calculated for each of the 10 stations indicated in Figure 1, for the period 1966–75. This ten-year period was chosen as it is likely to exclude large-scale effects due to changes in atmospheric transparency that may be associated with the changeover from solid fuel to oil, gas and electricity for use in industry, commerce and domestic heating (see Cowley, 1976). It was, however, a sufficiently long period for accurate estimates of the values a, a' and b to be obtained, approximately 300 data-pairs being used for each station-month correlation.

It was found that a and a' are independent of season, having values of about 0·24 and 0·15 respectively varying geographically by $\pm$0·02 over the United Kingdom. The pattern of variation of a and a' is similar to the variation of annual average global irradiation in Collingbourne's maps. The geographical variation of b is less well defined but the values of b are seasonal, increasing from about 0·50 in the winter to about 0·55 in the summer, the geographical variation being $\pm$0·05 about the mean value. The geographical variations of the annual values of a and a' and of the June and December values of b are shown in Figures 3 (a)–(d).

As indicated in Section 1, values of a, a' and b were assigned to each of 190 square regions of 40 km side, covering almost all the land area of Great Britain, values of a and a' being constant through the year and values of b estimated for each month.

The reliability of the subjective assignment of values of a, a' and b to the 40 km squares was tested for Kirkham (53°48′N, 02°53′W) for which daily irradiation and duration-of-sunshine data were available on punched cards for a 5-year period. Kirkham is remote from any of the radiation stations for which values of a, a' and b had been calculated, being 150 km from Sutton Bonington (52°50′N, 01°15′W), 170 km from Eskdalemuir (55°19′N, 03°12′W), 240 km from Aldergrove (54°39′N, 06°13′W) and 215 km from Aberporth (52°08′N, 04°34′W). Values of a, a' and b for the 40 km square that encloses Kirkham

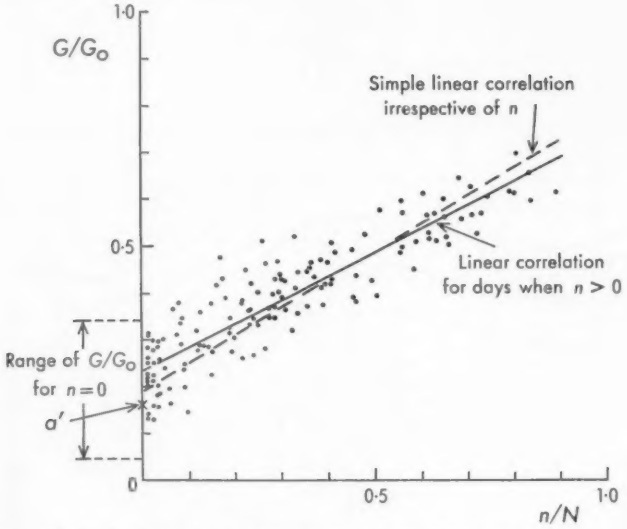

FIGURE 2(a)—COMPARISON OF TWO MODELS THAT RELATE GLOBAL SOLAR IRRADIATION TO THE DURATION OF BRIGHT SUNSHINE

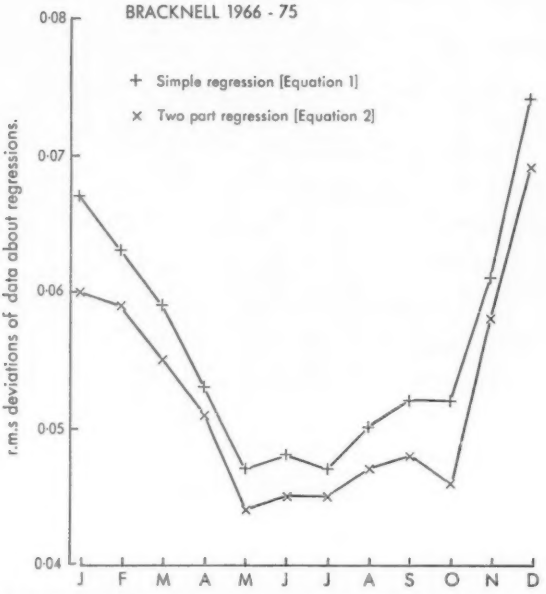

FIGURE 2(b)—ROOT-MEAN-SQUARE DEVIATIONS OF DATA ABOUT REGRESSION MODELS FOR EACH MONTH

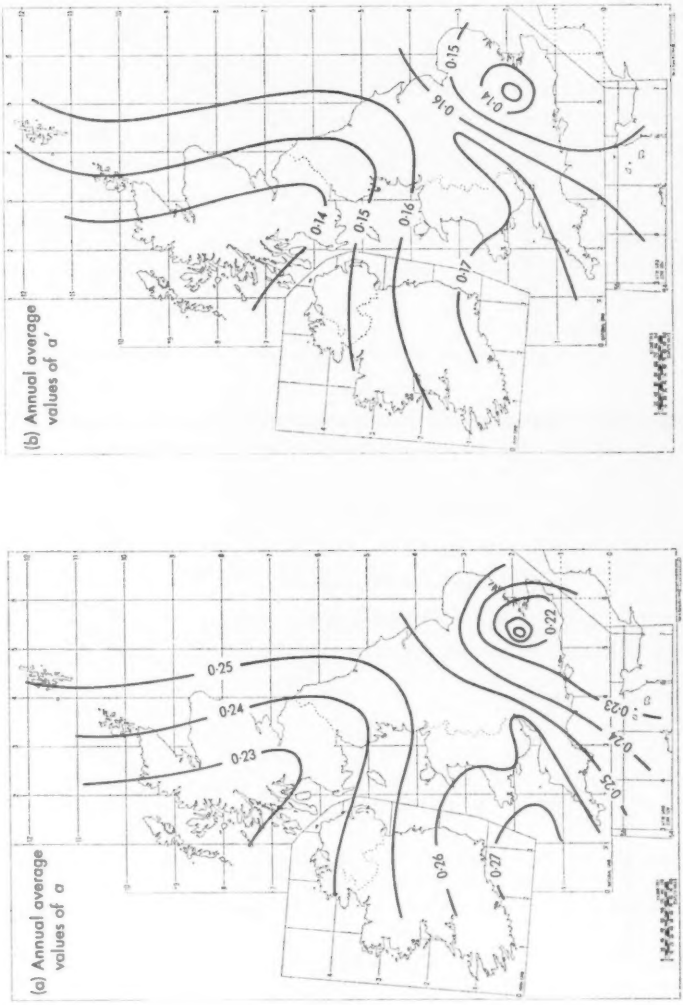

FIGURE 3—GEOGRAPHICAL VARIATIONS OF THE REGRESSION COEFFICIENTS

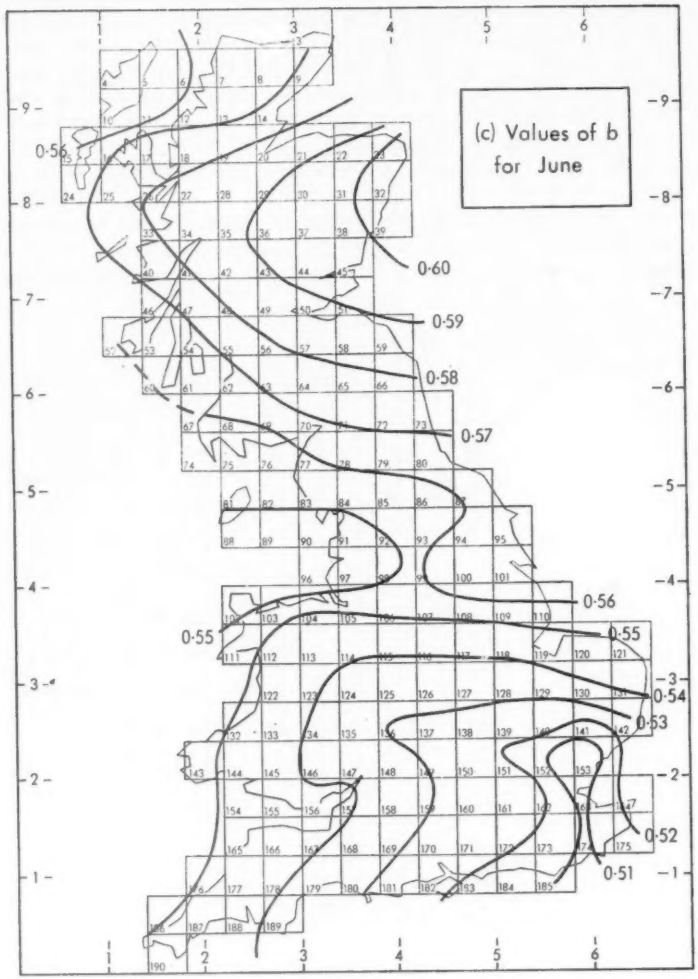

FIGURE 3—*continued*

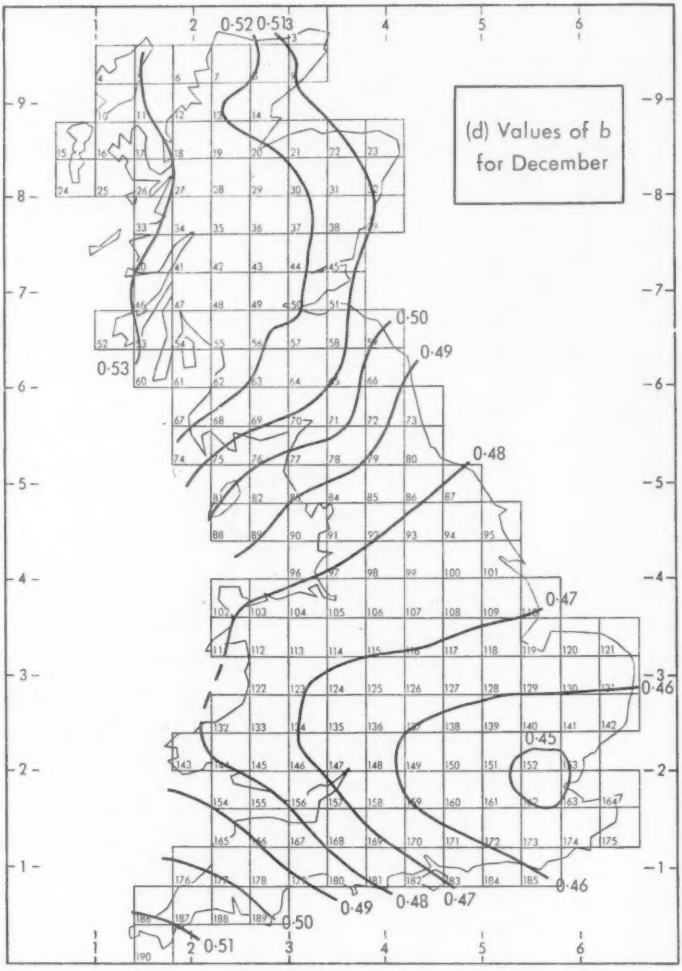

FIGURE 3—*continued*

were taken together with the sunshine data to estimate monthly global solar irradiations on a horizontal plane. The resulting correlation between predicted and measured irradiations is shown in Figure 4. Each point represents the data for a single month. The excellent agreement was taken as support for the validity of this work.

Only those stations whose sunshine data are available on computer magnetic tape were used to calculate estimates of global solar radiation in this work. The sunshine data for each of 132 stations were used to estimate the monthly irradiations from equation (2), using values of a, a' and b that apply to the square that encloses the station. A few stations (for example Tiree at 56°30′N, 06°53′W and Hastings at 50°51′N, 00°34′E) do not lie inside any of the 190 squares: values of the constants for these stations were estimates from the values assigned to the nearest squares.

Isopleths of equal irradiation were hand drawn both to the irradiations measured by stations indicated in Figure 1 and to those estimated by the procedure described here; the maps shown in Figures 5 (a)–(m) were thus obtained.

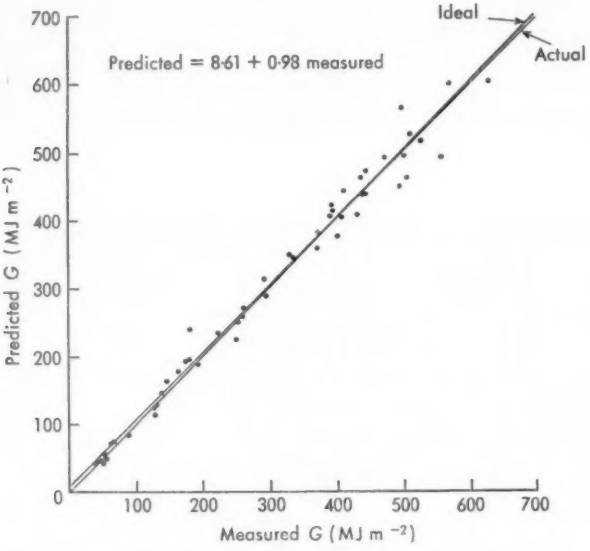

FIGURE 4—CORRELATION OF PREDICTED AND MEASURED MONTHLY GLOBAL SOLAR IRRADIATIONS FROM KIRKHAM, JULY 1968 TO DECEMBER 1973

4. DISCUSSION

The maps in Figures 5 (a)–(m) show the variation of global solar irradiation over Great Britain on a horizontal plane. It is seen that the pattern of isopleths shows three principal features:

(a) the general decrease in irradiation with increasing latitude: the seasonal change over Great Britain is less marked in summer than in winter as a result

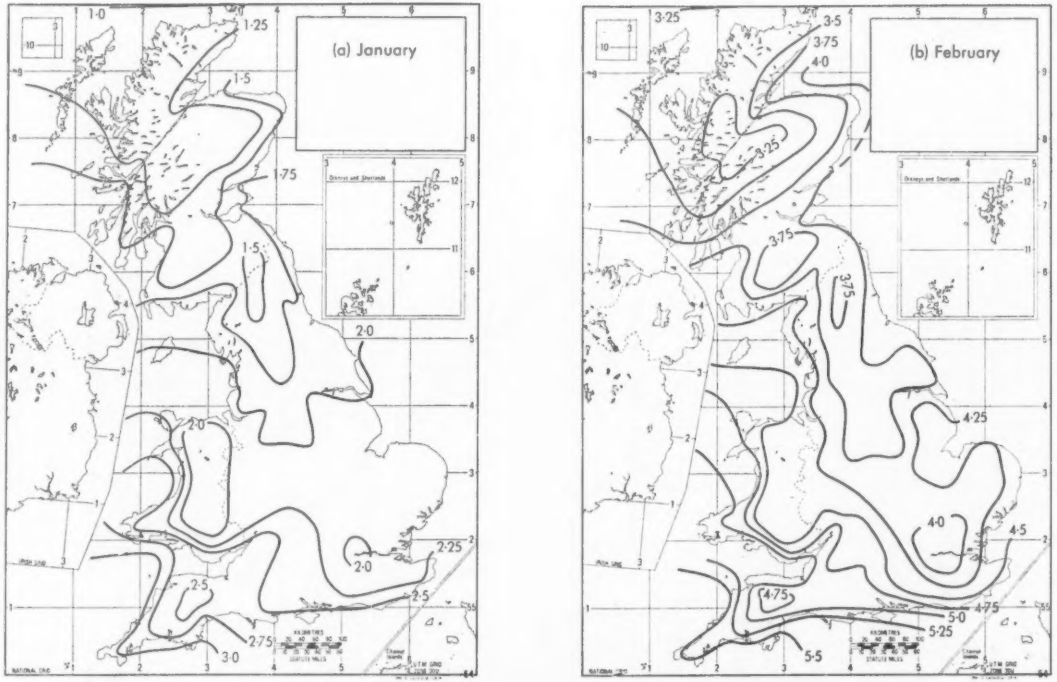

FIGURE 5—VARIATION OF MEAN DAILY GLOBAL SOLAR IRRADIATION OVER GREAT BRITAIN ON A HORIZONTAL PLANE

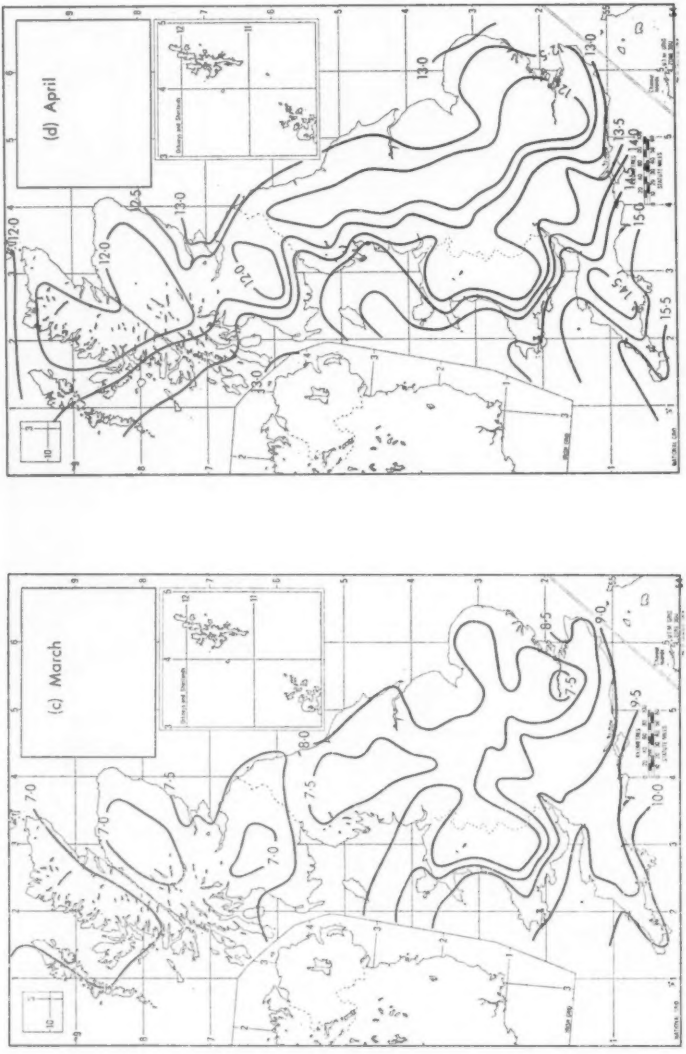

FIGURE 5—*continued*

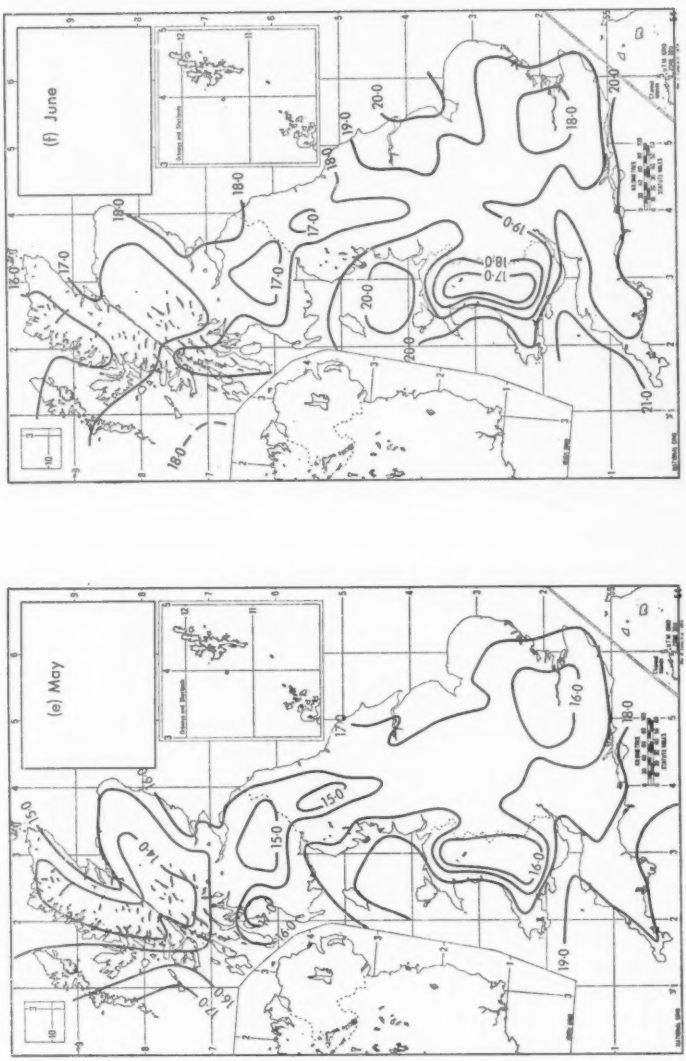

FIGURE 5—*continued*

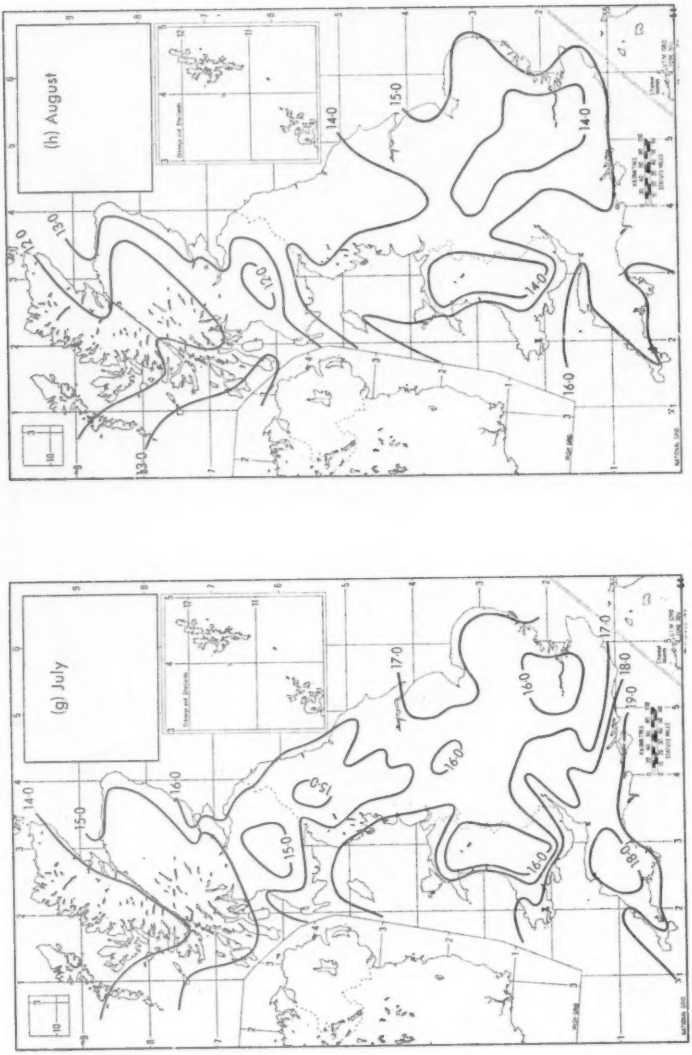

FIGURE 5—*continued*

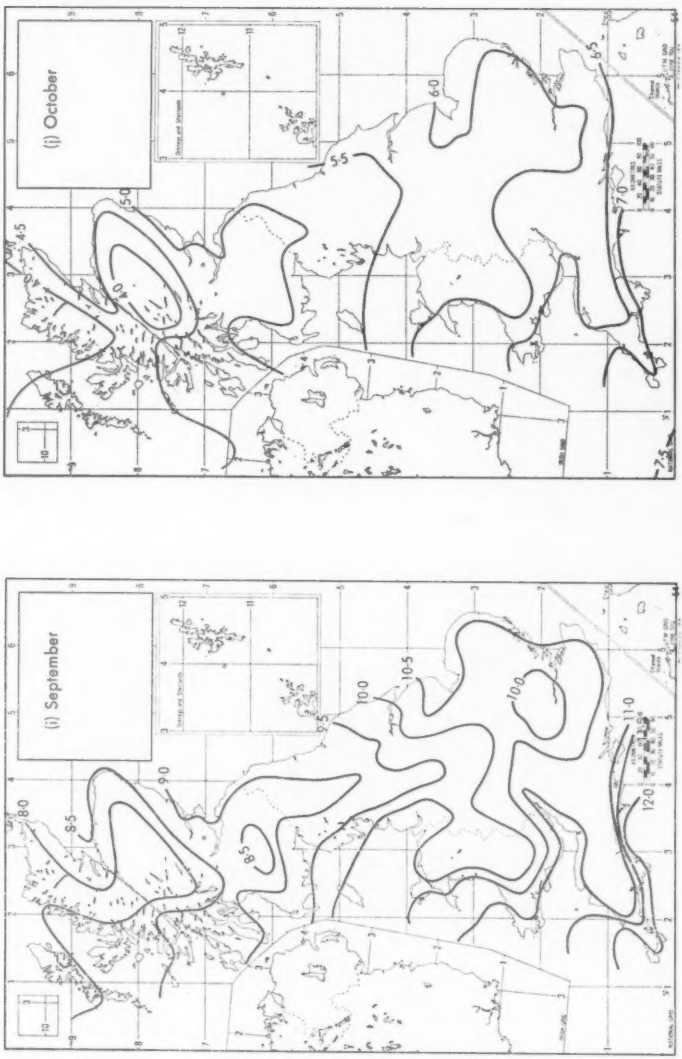

FIGURE 5—*continued*

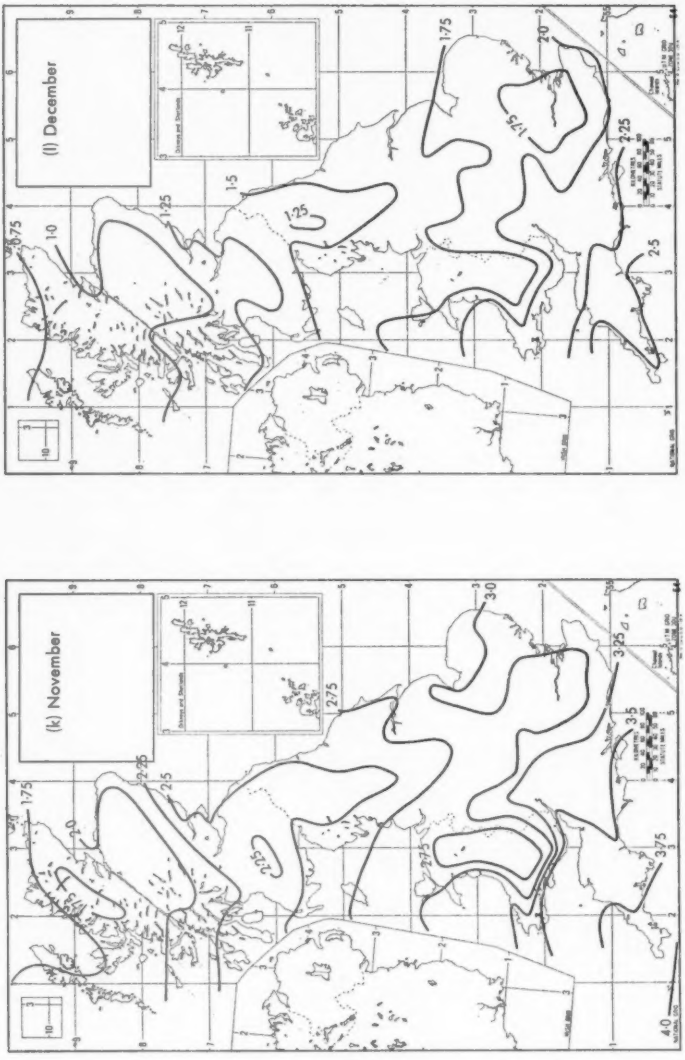

FIGURE 5—*continued*

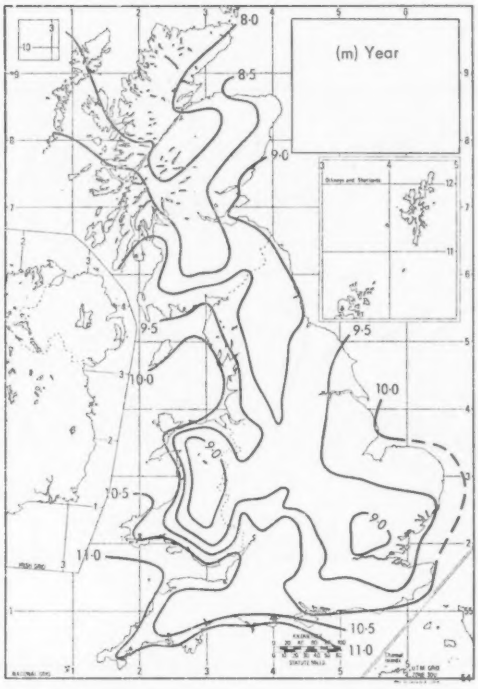

FIGURE 5—*continued*

of the longer days in the north compensating for the lower irradiances associated with greater solar zenith angles,

(b) the reduction of irradiation in inland areas associated with the increase in cloud amount, particularly over high ground, and

(c) the decrease in irradiation over a broad central area that covers the major conurbations.

The maps can only show the broad-scale features of the geographical variation; it would be erroneous to interpolate to high precision for particular locations, particularly those remote from radiation stations. The Meteorological Office has plans to enhance the distribution of recording equipment to monitor solar radiation: six radiosonde stations are to be equipped in the near future with MODLE 3 (Meteorological Office Data Logging Equipment) for this purpose and it is possible that global solar irradiation may be measured by up to 50 automatic weather stations located primarily in remote areas over the next 10 years. Only when these supplementary stations have been in operation for a decade will they be able to make possible a revision of the maps presented here. Until then little improvement is thought likely to be made.

Met.O.915

the meteorological magazine

1978 Volume 107

5. Conclusion

An improved correlation equation relating daily global solar irradiation to the duration of bright sunshine has been used to estimate the long-term monthly averaged irradiation from sunshine measured at a large number of stations. It has been shown that the technique of assigning correlation constants to 40 km squares over Great Britain works well for Kirkham, whose data were not used in deriving correlation constants.

Maps are presented which show the seasonal and geographical variation of global solar irradiation; little improvement is thought likely to be made until further radiation data become available.

6. Acknowledgements

The author gratefully acknowledges the help rendered by many people, including A. J. Ougham for his helpful discussions derived from his experience of the Campbell-Stokes sunshine recorder, and J. Arnott of the Agricultural and Hydrological Branch of the Meteorological Office for interpolating the correlation constants for the 190 square regions.

References

ÅNGSTRÖM, A. 1925 On radiation and climate. *Geogr Ann*, Stockholm, pp. 122–142.

CATON, P. G. F. and SMITH, C. V. 1977 Wind and solar radiation—availability in the United Kingdom. Presented at Conference on Ambient Energy in Building Design at the University of Nottingham, April 1977. To be published by the Construction Industry Conference Centre during 1978.

COLLINGBOURNE, R. J. 1976 Radiation and sunshine. Chandler, T. J. and Gregory, S. (editors), The climate of the British Isles, Longman, pp. 74–95.

COWLEY, J. P. 1976 Variations in global solar radiation at Kew. *Met Mag*, **105**, pp. 329–343.

DAY, G. J. 1961 Distribution of total solar radiation on a horizontal surface over the British Isles and adjacent areas. *Met Mag*, **90**, pp. 269–284.

METEOROLOGICAL OFFICE 1974 Maps of average duration of bright sunshine over the United Kingdom 1941–1970. (Unpublished, copy available in the Meteorological Office Library, Bracknell.)

551.509.329:551.596

A METHOD FOR THE PRODUCTION OF ACOUSTIC FORECASTS USING A DIGITAL COMPUTER

By R. T. SUGGITT

(Meteorological Office, Bracknell)

SUMMARY

Acoustic forecasting is a task that is performed operationally at three upper-air stations in the United Kingdom which provide meteorological support for Proof and Experimental Establishments and for military training ranges. These forecasts are currently done by hand, but the planned installation of minicomputers at these stations will allow the use of programs to produce, or to assist in the production of, acoustic forecasts. This paper discusses the background of this task, presents the approach that was taken in the development of an appropriate computer-based method, and describes the method itself.

INTRODUCTION

Three upper-air stations in the United Kingdom provide meteorological support for Proof and Experimental Establishments of the Royal Armament Research and Development Establishment, and for some firing ranges that are used for military training purposes. The staff at these stations are required, as a matter of routine, to make acoustic forecasts in order to predict the propagation of noise from gunfire and other surface detonations.

In some circumstances, if it is predicted that noise will be propagated towards populated or sensitive areas, firing will not commence; in others, particularly where training schedules may be disrupted, the forecasts are used in the retrospective verification of complaints and claims for blast-induced damage—for example the breakage of windows or other glass.

Normally these forecasts are done by hand, with data obtained from a recent radiosonde or pilot-balloon ascent, but the method involves a large amount of hand calculation and the production of a comprehensive forecast (that is to say for a full 360° about the firing point) is tedious and slow. In practice, therefore, the forecaster confines himself to the determination of what is known as the clear arc, and to the propagation of noise along a limited number of azimuths that are known to be sensitive. The clear arc is that set of directions towards which noise tends not to propagate.

In the near future these stations will be equipped with the new United Kingdom Mk 3 radiosonde system. In addition to the new radiosonde and new receiving and recording devices, each upper-air station will have a Ferranti Argus 700 E minicomputer. The details of the new hardware and of the computer software will not be given here: full accounts have been given by Hooper (1969) and Pettifer and Axford (1977) but some brief comments on the function of the minicomputer will be of value. This device is used during a radiosonde ascent to sample the coded data that are transmitted by the radiosonde, to apply quality control and calibration corrections to the data, to decode them, and to select from them the significant temperature and humidity values. The computer also interrogates a radar and uses the sets of azimuth, elevation, and slant range obtained to derive a wind profile for the ascent. The program that

is provided for synoptic stations then uses those significant points and the wind profile to assemble a standard TEMP message, and a set of archives. It must be stressed that the only time the operators actually see the meteorological data is when the TEMP message is punched out on paper tape. The upper-air stations supporting Proof and Experimental Establishments and firing ranges must, in order to allow them to fulfil their operational commitments, be supplied with a data processing program that will print out meteorological data at appropriate intervals. In particular, the computer must be programmed to print out sufficient data to permit the production of acoustic forecasts.

While these data could simply be a set of values of temperature, humidity, and wind speed and direction, requiring that forecasts should still be done by hand, it is clear that the computer could, in addition, process the data to produce a forecast in either an intermediate or a final form.

Apart from the fact that staff will be released from the tedium of doing a large number of calculations by hand and may be employed in more productive tasks, this system has the advantage that forecasts may be produced more rapidly and in a more comprehensive form than is currently possible. The forecasts will benefit in any case from the improved accuracy of the new radiosonde.

Production of sound foci

A detonation of explosive on or near the surface creates a diverging shock wave, starting from the point of the explosion and spreading in all directions. In the hemisphere above ground the shock waves degenerate to sound waves quite rapidly, and the paths of the various parts of the wave front can be depicted by rays emanating in all directions from the centre of the explosion. These sound rays are then refracted through the atmosphere and may return to the surface at a point that is distant from the source, and if several such rays return to the surface in close proximity a focus is said to occur. The amount of energy that returns to the surface at a focus may be greater by some orders of magnitude than that which reaches the surface where there is no focus, and may, depending on the size of the original explosion, cause damage to structures.

The propagation of noise caused by large accidental explosions has been studied since the turn of the century, when it was correctly inferred that the variations of audibility were caused by variations of the wind and temperature structure of the troposphere and stratosphere. One such explosion was that in 1921 at Oppau in Germany, where, to the east, observers 220 km away heard the explosion whereas those 120 km away did not. Another was that at Burton-on-Trent, England, in 1944, an account of which is given by Murgatroyd (1944). The noise of the explosion, which involved 7000 tons of high explosive, was heard up to 150 miles (240 km) away to the south-east, but only up to 50 miles (80 km) away to the north-west. To the east there was a zone of silence between 70 and 100 miles (112 and 160 km) away, while the explosion was heard at locations outside and inside the zone.

In contrast, the amount of explosive detonated at Proof and Experimental Establishments or practice ranges is usually small. It is generally assumed that the amounts of energy transmitted into the middle and upper troposphere are insignificant for acoustic forecasting purposes, and that the position of foci and other features is determined by the wind and temperature structure of the lowest two kilometres of the troposphere (Jackson, 1971; Caton, 1971; Lumley, 1971).

This will allow for the production of an acoustic forecast for areas up to 40 km from an explosion. Jackson, Caton, and Lumley provide a useful insight into the problems that are encountered in operational acoustic forecasting, and into the procedures that are in use.

The classical theory of the refraction of sound is well established and will not be reproduced in this paper; it is similar in principle to the theory of refraction of light, which is probably more widely known. The behaviour of a ray of light at the boundary of two media is determined by the velocity of light within each medium. Similarly, the behaviour of a sound ray, travelling along a given azimuth from a point source, is determined by the velocity of sound in the layers of the atmosphere traversed. The velocity of sound in still air is proportional to the square root of the absolute temperature, thus the velocity of a sound ray travelling along a given azimuth is the algebraic sum of the velocity of sound due to the temperature and the component of the wind velocity along that azimuth.

Although this provides a useful intuitive starting point it is of no direct practical value because the lower troposphere does not exhibit a series of isothermal layers. Clearly some approximations are necessary to model a complex atmosphere, and to accommodate the way in which the atmosphere is sampled, but it is possible to derive a set of differential equations which are reasonably concise (Gilbert, 1961). These equations are then solved by means of an analog computer. Melville (1971) and Reed (1956) describe the way in which a variety of these devices are used.

Some constraints

It was clear that, if a model were to be devised for implementation on the upper-air station minicomputers, it would have to conform to a number of constraints. This model would have to become a part of the general radiosonde data processing program, and for reasons of economy would have to utilize the smallest area of core-storage possible. The model would have to be powerful and generalized because it would not be possible to involve the storage of, and reference to, a large number of set acoustic situations that could otherwise be used as precedents. To achieve this a 'first principles' approach is needed. A first principles approach would also obviate the need to program the forecaster's experience and the rules-of-thumb that tend to be used, which would themselves require a large area of core-storage and an excessive time for program development.

There are some advantages in using a digital computer, the most important being its large capacity for performing arithmetic calculations. There is no real penalty, therefore, if the model that is used requires a great number of calculations to be made, providing there are not so many that an acoustic forecast takes an excessive time to compute. This would be the case if it were attempted to use the differential equations that were devised for an analog computer, solving them by means of Runge-Kutta or similar methods.

One other small point that must be noted is that it was not necessary to devise a method that yielded results which were significantly better or more accurate than those given by the manual method, for the simple reason that the manual results are generally adequate for operational use.

The model

The best approach to the problem of calculating acoustic forecasting data was thought to be the provision of a program that calculated the range of return to the surface of sound rays, of varying initial elevations, travelling along azimuths of 10°, 20° . . . 350°, 360°. Those ranges, and tables of the velocity of sound at set heights, would be printed out for the forecaster who could then isolate the clear arc and areas where focusing was likely. It should also be possible for the forecaster to estimate the severity and persistence of any foci.

This system relieves the forecaster from the tedium of himself calculating ranges of return to the surface, but allows him to apply his experience to the interpretation of the computed results, and so retains much of the flexibility that was inherent in the purely manual method. In addition, it has the advantage that the considerable experience of the forecaster is retained, which will be of value if, for some reason, it is necessary to make an acoustic forecast when a computer is not available.

The model which is to be used has a framework that is similar to the manual method. The lowest 1950 metres of the atmosphere are considered as being divided into 13 layers, each 150 m thick. At each boundary a value of virtual temperature is obtained by interpolation from the two significant temperature points that overlap it, and a wind velocity is obtained by evaluating a mean wind within a 150 m layer that is centred on the given boundary.

It was found that, in order to achieve realistic results using 150 m layers, it was essential to consider the path of a sound ray as being curved. It was possible to assume a straight ray path if layers of 50 m were used, but this presents problems where wind evaluation is concerned, as the mean wind of a 50 m layer usually has a high 'noise' component.

It is possible to show (Gilbert, 1961) that a sound ray travelling along a given azimuth and traversing a layer of any thickness, but within which the sound velocity gradient is uniform, following a path that is an arc of a circle having its centre V_1/K below the layer, where

V_1 is the net velocity of sound at the lower boundary of the layer and
K is the sound velocity gradient within that layer.

This is illustrated in Figure 1.

Clearly this result may be applied if it is assumed that the sound velocity gradient within any 150 m is uniform. A method for acoustic forecasting based on this principle has been devised and tested, and has given results that seem reasonable, and comparable with those derived manually. A fuller description is given below.

Consider layer m that has a lower boundary m and upper boundary $(m + 1)$. A ray traversing this layer along a given azimuth will follow a path that is the arc of a circle with its centre D_m below boundary m, where

$$D_m = \frac{(V_m + A_m) \times \Delta h}{(V_{m+1} + A_{m+1}) - (V_m + A_m)},$$

and where

V_m is that component, along the given azimuth, of the wind velocity at boundary m,
A_m is the speed of sound in still air at boundary m,
Δh is the thickness of the layer (150 m).

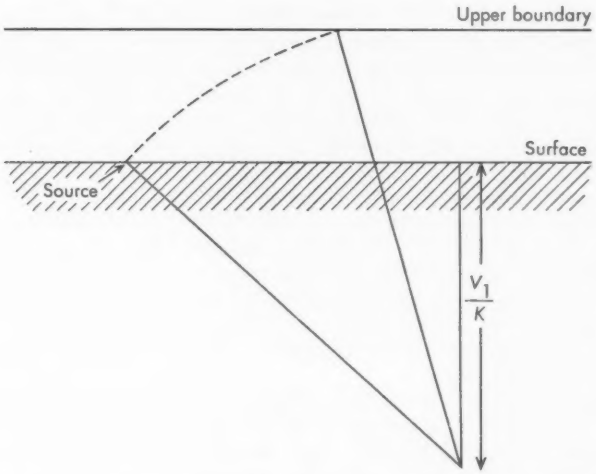

FIGURE 1—BEHAVIOUR OF A SOUND RAY, EMANATING FROM A POINT SOURCE, IN A LAYER WITH A SINGLE POSITIVE SOUND VELOCITY GRADIENT

Note that $A_m = 20{\cdot}05446\ \sqrt{T_m}$, where T_m is the absolute virtual temperature at boundary m, and V_{m+1} and A_{m+1} are defined as V_m, A_m for boundary $(m + 1)$.

The convention that then applies is that for a positive sound velocity gradient (i.e. if the sound velocity is greater at the upper boundary than at the lower), D_m is positive and the centre of curvature is below the lower boundary, so the ray curves downwards. If the gradient is negative, D_m is negative and the centre of curvature is above the lower boundary so the ray curves upwards. See Figure 2.

To trace the path of a sound ray along a given azimuth the following procedure is used. The lowest layer (layer 1) is considered, and the existence of a sound ray of initial elevation E_1 is assumed; it is possible then to calculate the elevation E_2 of the ray at its point of entry into layer 2, and the distance travelled (in a horizontal sense), ΔR_1. See Figure 3. This operation is repeated for layer 2, assuming that the elevation of the ray is E_2 and that the centre of curvature is D_2 below boundary 2, to calculate ΔR_2 and E_3.

This is continued for each layer in turn until the ray either becomes horizontal, escapes from the top layer, or attains an elevation greater than 20° and so cannot possibly return to the surface. If the ray becomes horizontal, when

$$D_i\,(1 - \sec E_i) < \Delta h$$

for some layer i, the range of return to the surface, R, may be evaluated as

$$R = 2 \sum_{m=1}^{i} \Delta R_m.$$

The ray tracing process is performed a number of times to give a comprehensive forecast for the azimuth under consideration. On the first occasion a ray

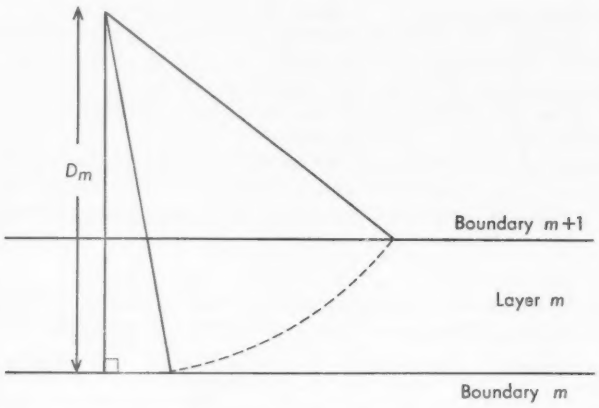

FIGURE 2—BEHAVIOUR OF A SOUND RAY IN A LAYER WITH A SINGLE NEGATIVE SOUND VELOCITY GRADIENT

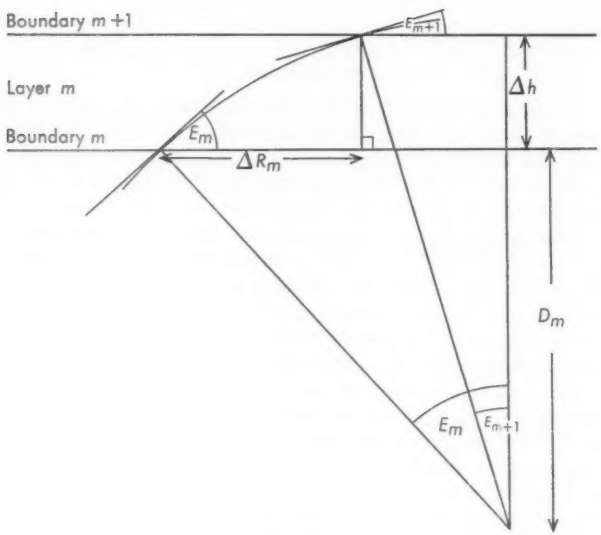

FIGURE 3—CALCULATION OF ELEVATION AT TOP OF LAYER, E_{m+1}, AND HORIZONTAL DISTANCE TRAVELLED, ΔR_m

having an initial elevation of 1° is taken. If it returns to the surface, a ray with an initial elevation of 2° is taken, continuing with rays of initial elevation of 3°, 4° etc., until a ray diverges from the surface (i.e. escapes from the top layer or attains an elevation of 20° or more). Finally, in order to provide a comprehensive forecast for a complete 360° of arc, the above procedure is performed for azimuths of 0°, 10°, 20°, . . . 350° in turn.

In order to add an illustration of the use of the model, an example of a typical radiosonde sounding is shown in Table I. Table II gives the model output which is set out in a similar manner to that which will be produced by the operational version.

TABLE I—WIND AND TEMPERATURE DATA FROM A RADIOSONDE ASCENT LAUNCHED AT BEAUFORT PARK AT 10 GMT ON 24 AUGUST 1977

Height above ground *metres*	Wind speed m/s	Wind direction *degrees*	Temperature °C
0	5·1	100	14·9
150	9·3	116	13·1
300	13·5	131	12·1
450	17·7	147	10·8
600	18·2	156	9·4
750	18·7	162	8·6
900	19·1	168	7·5
1050	19·7	175	6·3
1200	20·5	179	5·2
1350	21·7	182	4·4
1500	22·5	188	3·9
1650	22·1	202	5·2
1800	21·7	216	5·6
1950	21·2	229	5·6

REFINEMENTS

There are clearly a number of refinements that could be made to the model described above, some of which will be discussed here. They fall into two main groups, those that were not made because they do not appear to be operationally significant, and those that may be more easily performed by a forecaster.

Warren (1964) points out that the direction of travel of a sound ray is not the direction of the normal to the wave-front, which was an assumption made in producing the expression for D. The result quoted in the preceding section is therefore incorrect, the formula for D being more complex. However, in this application the error is small since only low elevation rays are involved, Warren's findings applying more to the propagation of noise from sonic boom and large (thermonuclear) explosions. This has been confirmed by a series of tests which show that, although the position of one or two ray returns is displaced by up to 1 km, the overall pattern of ray returns is unchanged.

Diamond (1964) explains techniques for determining the cross-wind effect on a sound ray, and by implication on the position of ray returns and foci. Cross-wind corrections were not made, however, because it was felt that the errors in the position of ray returns were small, and also because no such corrections are made in a manual forecast. It will be remembered that it was stated earlier that it was not intended to derive results significantly better than those which could be derived manually.

TABLE II—RESULTS GIVEN BY MODEL FOR RANGE OF RETURN OF SOUND RAYS

	Initial elevation (degrees)																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Azimuth (degrees)	*Range in kilometres*																	
10	1·2	2·4	3·6	4·8	5·9	5·2	5·1	5·3	5·5	5·8	5·6	5·8	5·9	6·2	12·9	23·2	27·6	—
20	2·2	4·5	6·7	7·6	5·9	5·7	5·8	6·1	6·1	5·9	6·0	6·1	6·3	10·3	15·4	21·0	23·6	—
30	21·7	10·2	7·8	7·0	6·8	6·9	7·1	6·5	6·4	6·4	6·5	7·9	10·2	13·4	17·1	21·7	21·7	21·1
40	10·6	9·5	8·9	8·8	8·0	7·3	7·1	7·0	7·0	7·2	9·5	11·4	14·1	16·1	19·9	20·7	19·4	18·5
50	10·7	9·8	9·1	8·6	8·3	8·1	8·1	9·0	10·0	11·4	13·1	15·3	15·9	20·1	20 0	18·9	17·3	18·0
60	11·2	10·7	10·3	10·6	10·8	11·1	11·5	13·0	14·2	15·6	15·8	18·7	21·1	19·4	17·6	16·4	15·8	17·1
70	14·6	14·5	14·5	14·7	15·0	15·7	16·4	16·2	16·4	20·4	22·4	19·5	17·9	16·4	15·7	15·4	15·8	17·4
80	18·5	18·1	17·9	17·7	17·7	20·9	23·0	21·9	20·4	19·9	17·4	16·3	15·6	15·1	15·2	15·2	16·0	17·1
90	24·1	23·4	22·7	22·1	21·6	19·9	18·5	17·5	16·7	16·0	15·5	15·0	15·0	14·9	14·8	15·6	16·1	—
100	17·2	18·8	18·3	17·8	17·3	16·8	16·3	15·8	15·6	15·3	15·1	14·9	14·7	15·2	15·4	—	—	—
110	17·6	17·3	17·0	16·7	16·4	16·1	15·8	15·5	15·3	15·1	15·2	15·3	15·3	—	—	—	—	—
120	17·3	17·0	16·7	16·4	16·1	16·0	15·9	15·8	15·7	15·6	—	—	—	—	—	—	—	—
130	17·6	17·3	17·1	16·8	16·6	16·4	—	—	—	—	—	—	—	—	—	—	—	—
140	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
150	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
160	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
170	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
180	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
190	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
200	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
210	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
220	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
230	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
240	7·8	15·7	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
250	1·8	3·7	5·5	7·4	—	—	—	—	—	—	—	—	—	—	—	—	—	—
260	1·1	2·2	3·2	4·3	5·4	14·2	—	—	—	—	—	—	—	—	—	—	—	—
270	0·8	1·6	2·4	3·2	4·0	4·8	7·2	9·5	—	—	—	—	—	—	—	—	—	—
280	0·6	1·3	1·9	2·6	3·3	3·9	4·6	6·0	7·2	—	—	—	—	—	—	—	—	—
290	0·6	1·1	1·7	2·3	2·9	3·4	4·0	4·8	5·6	6·3	12·5	—	—	—	—	—	—	—
300	0·5	1·0	1·6	2·1	2·6	3·2	3·7	4·2	4·8	5·4	5·9	8·6	—	—	—	—	—	—
310	0·5	1·0	1·5	2·0	2·5	3·1	3·6	4·1	4·4	4·9	5·3	6·3	7·5	—	—	—	—	—
320	0·5	1·0	1·5	2·0	2·5	3·1	3·6	4·1	4·3	4·6	5·0	5·4	6·3	7·0	—	—	—	—
330	0·5	1·1	1·6	2·1	2·7	3·2	3·8	4·3	4·3	4·6	4·9	5·3	5·8	6·3	—	—	—	—
340	0·6	1·2	1·8	2·3	2·9	3·5	4·1	4·3	4·4	4·7	5·0	5·3	5·6	6·0	6·3	—	—	—
350	0·7	1·3	2·0	2·7	3·4	4·0	4·7	4·4	4·6	4·9	5·2	5·4	5·6	5·9	6·2	—	—	—
360	0·8	1·7	2·5	3·4	4·2	5·0	4·7	4·7	5·0	5·3	5·5	5·5	5·7	5·9	11·0	38·7	—	—

Data in Table I are used as input. Dashes represent rays that do not return to the surface. Note the existence of a clear arc between 140° and 230°, the foci at about 15 kilometre range between 070° and 130°, at about 5 kilometres between 360° and 040°, and up to 5 kilometres between 260° and 350°.

The assumption that the sound velocity gradient within any layer 150 m thick is uniform may be questioned. It is agreed that the choice of 150 m layers represents a compromise between the use of a limited number of thick layers, for which meteorological data, especially representative wind data, may be obtained conveniently, and the use of a large number of thin layers for which the assumption is valid but for which it would be difficult to derive representative data. It may be preferable in some circumstances to use variable layers, choosing the height of the boundaries such that the sound velocity gradient within any layer *is* uniform. This is not possible for the situation here, however, because of the limitations in the area of core-storage that is available, and because the data selection programs would have to be particularly complex.

There are other reasons for not including the refinements mentioned previously. Murgatroyd (1944) explains that 'although the main characteristics of the sound propagation are determined by the wind and temperature variations with height, it would not be expected that the various zones of audibility would be well marked . . . the effects of scattering and diffraction . . . are likely to be considerable'.

In practice, therefore, it is not possible to predict the exact limits of areas in which a focus occurs, as the scattering and diffraction of sound rays (caused probably by mechanical turbulence) will blur them. Indeed, perhaps the word focus is something of a misnomer. Furthermore, when acoustic forecasts are made, they are generally expected to remain valid for up to three hours because the state of the atmosphere does not normally change markedly in this period, and also because of the great difficulties that would arise if forecasts had to be produced at shorter intervals. Within a two to three hour period, however, small changes do occur in the temperature and wind structures, owing to the natural spatial and temporal variability of the atmosphere. It is accepted that a forecast can only be valid in general terms, and that the position of the clear arc and any foci are only approximate, assuming probable errors of about $\pm 10°$ and ± 2 km respectively.

It is clear then that the value of additions to the model which attempt to improve its accuracy is very limited.

Other refinements were not made to the model because it was thought that they were best left to a forecaster. One of these is known as skipping, or the formation of multiple reflections. This occurs when the attenuation of noise at a focus is low, which tends to happen if a focus is formed at a water surface. The focus can, in this situation, act as a secondary source and create an additional set of foci, which would result in the noise of a explosion being carried for many kilometres. Other refinements not included are the calculation of overpressures associated with foci, the effect of an undulating terrain on the position of foci, and the limits of what Murgatroyd calls the audibility bowl (the area within which a grazing sound ray is available).

Conclusion

It is hoped that this paper has provided an adequate summary of the theoretical problems that apply to acoustic forecasting, and of the method that will be used when the Mk 3 radiosonde comes into service at the upper-air stations providing support for Proof and Experimental Establishments and practice ranges.

The use of a ray-tracing approach, in which the path of each ray in each layer is considered, will readily accommodate multi-gradient atmospheres, and so will eliminate some of the approximations that have to be made manually when multi-gradient atmospheres occur. It is impossible, however, to estimate how valuable this and other potential improvements are when forecasts are made operationally for periods of up to two or three hours. The natural spatial and temporal variability of the atmosphere is usually the dominant factor in this period.

It is certain, however, that the forecaster will be spared the tedium of making a large number of calculations by hand, which should allow him to concentrate primarily on the task of interpreting the simple results printed out by the computer. It should therefore be possible in the near future to make acoustic forecasts more rapidly and in a more comprehensive form, which will, it is hoped, be of benefit both to the official establishments and to the public at large.

References

CATON, P. G. F. 1971 Acoustic forecasting. London, Min Def CSR(A), *Instr Serv Tech Note* 1/71, pp. 103–104.

DIAMOND, M. 1964 Cross wind effect on sound propagation. *J Appl Met*, **3**, pp. 208–210.

GILBERT, G. H. 1961 An approach to the quantitative production of anomalous blast effects. *J Appl Met*, **1**, pp. 102–106.

HOOPER, A. H. 1970 Some features of the new United Kingdom radiosonde. Geneva, WMO. Upper-air instruments and observations, WMO No. 284, pp. 364–377.

1970 Problems in the automatic computation of radiosonde data. Geneva, WMO. Upper-air instruments and observations. WMO No. 284, pp. 347–363.

JACKSON, F. C. 1971 Acoustic forecasting at P & EE Shoeburyness. London, Min Def CSR(A), *Instr Serv Tech Note* 1/71, pp. 105–111.

LUMLEY, P. D. 1971 Noise problems on Salisbury Plain. London, Min Def CSR(A), *Instr Serv Tech Note* 1/71, pp. 121–122.

MELVILLE, S. 1971 Background notes on the use of a purpose built computer to aid acoustic forecasting at AWRE Foulness. London, Min Def CSR(A), *Instr Serv Tech Note* 1/71, pp. 113–120.

MURGATROYD, R. J. 1944 The audibility of the Burton-on-Trent bomb dump explosion. (Unpublished, copy available in the Meteorological Office Library, Bracknell.)

PETTIFER, R. E. W. and AXFORD, D. N. 1977 A new, fully automatic radiosonde ground-station for use with the United Kingdom Mk 3 radiosonde. WMO Technical Conference on Instruments and Methods of Observation (TECIMO), Hamburg 1977, WMO No. 480, pp. 19–24.

REED, J. W. 1956 Weather determines blast prediction for atom tests. *Weatherwise*, **9**, pp. 202–203.

WARREN, C. H. E. 1964 A note on the refraction of sound in a moving gas. *J Sound Vib*, **1**, pp. 175–178.

REVIEW

A meteorological study of July to October 1588: the Spanish Armada storms (*Research Publication* No. 6), by K. S. Douglas, H. H. Lamb and C. Loader. 295 mm × 210 mm, pp. 76, *illus.* Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, 1978. Price: £2.85 plus postage and packing.

The stormy weather which had such an adverse effect on the Spanish Armada in 1588 is described and interpreted in a sequence of synoptic weather charts for the period. Although the interpretation is sometimes open to serious doubt especially near the western edge of the charts, the central parts of the analyses appear generally well-founded. The reader can form an opinion on each chart by consulting the extensive table of weather reports. This table also includes the authors' interpretation of the reports in terms of synoptic situations.

The interpretation of various features, such as sea fog and preferred frontal positions, in terms of atmospheric and oceanic circulations which could have been typical of the 'Little Ice Age' is interesting and feasible. Unfortunately the reviewer finds the Scandinavian cold front on Figure 9, mentioned in this context, to be rather speculative, but other charts mentioned seem better founded. The discovery of Tycho Brahe's records for Denmark is of great value for our knowledge of late 16th century climate.

The variable v_G in the two equations on page 9 should be the observed warm sector surface wind over the ocean. If it were the gradient wind then in equation (ii) V_y would always exceed 0·6 × the gradient wind and would not be only half the gradient wind as stated in the text. Table 4 is consistent with the use of surface wind in the equations.

The study will be of interest to historians and meteorologists and has helped to improve our understanding of the climate of North-west Europe in the late 16th century.

D. E. PARKER

NOTES AND NEWS

Launch of the United States operational weather satellite, TIROS-N

TIROS-N, the first of the third generation of United States polar-orbiting operational meteorological satellites was launched from the Western Test Range, California on 13 October. Whilst these satellites will, like their predecessors, provide cloud imagery and measurements of atmospheric temperature structure, improved instruments and an extended range of measurements should provide significant improvements in the quality of these products. For instance, the instrumentation for determining temperature structure comprises an infra-red radiometer with a spatial resolution of about 20 km which has 20 spectral

channels, a 3-channel stratospheric radiometer, and a 4-channel microwave radiometer, which together should lead to an improvement in the accuracy of temperature retrievals particularly in the presence of cloud. The payload also includes a telecommunication package which will locate and collect messages from the constant level balloons and drifting buoys being deployed in conjunction with the First GARP Global Experiment.

For the first time instruments provided by the United Kingdom and France are being used on a United States operational meteorological satellite. The United Kingdom's contribution is the Stratospheric Sounding Unit (SSU) provided by the Meteorological Office. This is an infra-red radiometer which will provide information on a global scale about the temperature structure in the stratosphere at heights between 25 and 50 km. Its observations are processed in Washington in conjunction with data from two other radiometers on the satellite to provide the routine atmospheric temperature profiles. The SSU data are also transmitted to the Meteorological Office where they are processed and used for research purposes.

The design of the SSU is based on the principle of 'selective chopping' exploited by Oxford, Reading and Heriot Watt University instruments on earlier United States experimental satellites. The experience gained has made the United Kingdom a leader in this field and was the main reason for the selection of the SSU as part of the TIROS-N instrument package. The SSUs have been developed and manufactured by Marconi Space and Defence Systems at Frimley. Some of the most critical components, the detectors, were made at Plessey's Allen Clark Research Centre, Caswell.

OBITUARY

We regret to record the death of Mr H. M. Keenan, Port Meteorological Officer in Glasgow, on 8 July 1978.

Mr Keenan, who was born and educated in Glasgow, joined the ocean weather ship service of the Meteorological Office as 3rd Officer in April 1969 after more than 25 years' experience as a merchant navy officer with Anchor Line and in the coastal trade between Scotland and Ireland. He was promoted to established 2nd Officer the following December and thereafter sailed frequently as Acting Chief Officer. In March 1972 he was appointed Port Meteorological Officer in Glasgow, where he remained until his death. He will be remembered for his lively sense of humour as well as for his devotion to duty.

We record with regret the death on 5 September 1978 of Miss A. M. Peters, Assistant Scientific Officer, of the Agriculture and Hydrology Branch.

Miss Peters joined the Office in September 1944 and worked in a number of outstations and Headquarters branches.

THE METEOROLOGICAL MAGAZINE

NO. 1277 DECEMBER 1978 VOL. 107

CONTENTS

Page

The distribution over Great Britain of global solar irradiation on a horizontal surface. J. P. Cowley 357

A method for the production of acoustic forecasts using a digital computer. R. T. Suggitt 374

Review

A meteorological study of July to October 1588: the Spanish Armada storms (Research Publication No. 6). K. S. Douglas, H. H. Lamb and C. Loader. *D. E. Parker* 384

Notes and news

Launch of the United States operational weather satellite, TIROS-N .. 384

Obituary 386

NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ, and marked 'For Meteorological Magazine'.

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

Complete volumes of 'Meteorological Magazine' beginning with Volume 54 are now available in microfilm form from University Microfilms International, 18 Bedford Row, London WC1R 4EJ, England.

Full size reprints of out-of-print issues are obtainable from Johnson Reprint Co. Ltd, 24–28 Oval Road, London NW1 7DX, England.

Issues in Microfiche starting with Volume 58 may be obtained from Johnson Associates Inc., P.O. Box 1017, Greenwich, Conn. 06830, U.S.A.

© *Crown copyright* 1978

Printed in England by Heffers Printers Ltd, Cambridge
and published by
HER MAJESTY'S STATIONERY OFFICE

£1 monthly **Annual subscription £13.14 including postage**

Dd. 595890 K15 12/78

ISBN 0 11 724806 1
ISSN 0026–1194